

Dynamic Spectrum Management for Upstream Mixtures of Vectored & Non-Vectored DSL

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Abstract— As field trials and initial deployments of Vectored DSL systems materialize in the next few years, Vectored DSL systems will often co-exist with non-vectored DSL systems sharing the same cable. For such mixed-binder scenarios with vectored and non-vectored lines, this paper presents an optimal Dynamic Spectrum Management (DSM) technique referred to as Mixed-binder Optimum Spectrum Balancing (MixOSB) to find the optimal transmit PSD spectra. When the mixed-binders have short vectored lines and long non-vectored lines, simulations show that MixOSB has substantial performance gains over applying existing DSM techniques independently to the vectored DSL systems and non-vectored DSL systems because it reduces the interference induced by the vectored lines on the non-vectored lines. The high computational complexity of MixOSB prohibits its practical implementation. So, a low-complexity practically-implementable Mixed-binder Multi-level Water-filling (MixMLWF) algorithm is proposed and simulations show its performance is close to the solution given by MixOSB.

I. INTRODUCTION

Vectored transmission in Digital Subscriber Line (DSL) systems increases the achievable data rates on a single copper twisted-pair dramatically through cancellation of the crosstalk, which is a limiting factor in DSL performance [1], [2], [3]. Achievable data-rates of up to 100 Mbps have already been confirmed in Vectored DSL system prototypes [4]. A standard for Vectored DSL was also published recently [5]. As the operators conduct field trials and initial deployments, Vectored DSL lines will often be expected to share DSL cable binder with existing non-vectored DSL systems (most commonly VDSL2 [6]). This can be the case for two reasons: At least in the initial phases of Vectored DSL deployment, operators will be unwilling to replace the existing DSL equipment. A probable scenario is that VDSL2 and Vectored DSL systems will be deployed from the same DSL access node and will be sharing DSL cable binders. Additionally, in geographies with loop unbundling, an operator with Vectored DSL systems may share binders with an operator that is using (non-vectored) VDSL2 systems, but with no plan for upgrading to Vectored DSL.

Several DSM strategies have been proposed for mitigating crosstalk in non-vectored DSL systems [7], [8], [9] and for cancelling crosstalk in the vectored DSL systems [1], [2], [3]. However, no results were publicly available until recently for mixtures of vectored DSL and non-vectored DSL systems. So, in mixed binders with vectored and non-vectored DSL

lines, the network operators may use existing DSM techniques on vectored DSL systems and non-vectored DSL systems independently, and then, transmit PSD spectra will converge in an iterative manner as in the case of iterative water-filling [7] in non-vectored DSL systems. This technique is referred to as Mixed-binder Iterative Water-filling (MixIWF) in this paper.

When DSM techniques are applied independently to vectored and non-vectored DSL systems in mixed-binder scenarios, the vectored systems can cancel crosstalk from non-vectored lines using a zero-forcing generalized decision feedback equalizer (ZF-GDFE) in upstream transmission [3]. However, the non-vectored lines can suffer from large crosstalk induced by the vectored lines running at very high data-rates, especially when the vectored lines are short and the non-vectored lines are long. An investigation of practical DSM techniques to reduce the crosstalk effects into the non-vectored lines was very recently presented by us in [10], specifically focusing on upstream transmission.

In this paper, an optimal DSM solution is presented for these mixed binder scenarios based on Optimum Spectrum Balancing [8] and is referred to as Mixed-binder Optimum Spectrum Balancing (MixOSB). MixOSB finds the optimal transmit PSD spectra for the vectored and non-vectored lines in mixed-binder scenarios, where the vectored lines use a zero-forcing generalized decision feedback equalizer (ZF-GDFE) with a fixed decoding order for the lines. The data-rates of non-vectored lines using MixIWF are found to be significantly lower compared to MixOSB when vectored lines induce significant FEXT into the non-vectored lines, especially when the vectored lines are short and non-vectored lines are long. These results are similar to the tradeoffs observed in near-far scenarios for spectrum-balancing in non-vectored DSL systems [8]. The computational complexity of MixOSB prohibits its practical implementation. So, a practically implementable low-complexity algorithm, referred to as Mixed-binder Multi-level Water-filling (MixMLWF), is proposed for such mixed binders with short vectored and long non-vectored lines. It is shown that the performance of MixMLWF is very close to MixOSB.

II. SYSTEM MODEL

The system model used in this paper for investigating the co-existence of Vectored and non-vectored DSL systems is shown

in Fig. 1. A multi-user multicarrier system with N subchannels and $K_1 + K_2$ DSL lines is considered with one transmitter and receiver for each DSL line. There are K_1 lines originating at the non-vectored DSL access node, and K_2 lines originating at the Vectored DSL access node. The non-vectored lines always use VDSL2 [6] technology, and the two access nodes are co-located. The $K_1 + K_2$ lines are assumed to be within the same DSL cable binder and are thus experiencing crosstalk. The access nodes are connected to a spectrum management center (SMC), and thus, the connected lines have their physical layer control parameters programmed by the SMC [11].

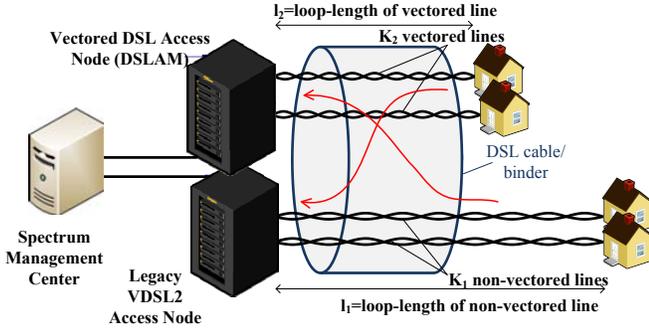


Figure 1. Mixed deployment of Vectored and Non-Vectored DSL, with K_1 lines using non-vectored DSL (VDSL2) and K_2 lines using Vectored DSL.

The multi-pair channel model for upstream transmission is as defined in [1]. The DSL system employs frequency-division duplexing and hence there is no interference from downstream into upstream. Each DSL line corresponds to a DSL user. Assuming there is no intercarrier interference and that the users are synchronized, the channel can be modeled as N parallel and independent subchannels. The channel model on any subchannel n is given by

$$\begin{aligned} \begin{bmatrix} \mathbf{y}_1^n \\ \mathbf{y}_2^n \end{bmatrix} &= \begin{bmatrix} H_{11}^n & H_{12}^n \\ H_{21}^n & H_{22}^n \end{bmatrix} \begin{bmatrix} \mathbf{x}_1^n \\ \mathbf{x}_2^n \end{bmatrix} + \begin{bmatrix} \mathbf{z}_1^n \\ \mathbf{z}_2^n \end{bmatrix}, \\ \mathbf{y}^n &= \mathbf{H}^n \mathbf{x}^n + \mathbf{z}^n. \end{aligned} \quad (1)$$

Here \mathbf{x}^n and \mathbf{y}^n denote the vector of transmitted and received samples respectively (each element corresponding to a different line), \mathbf{z}^n is the vector of received noise samples, and \mathbf{H}^n is the channel transfer matrix at the specified subchannel n . The background noise \mathbf{z}^n is assumed to be Gaussian with zero mean and diagonal noise covariance Σ_z , where $(\sigma_k^n)^2$ is the k -th diagonal element representing the noise variance of k -th user. The diagonal elements of the channel transfer matrix are defined using the transmission line model specified in [12] and the off-diagonal elements of the channel transfer matrix are defined using the 99% worst-case FEXT model specified in [12].

For upstream transmission on the vectored lines, signal-level coordination is possible at the receiver because they are co-located at a central office (CO) or an optical network unit (ONU). The channel transfer function H_{22}^n for these vectored lines can be modeled by a multiple-access channel (MAC)

with K_2 transmitters and K_2 co-located receivers. For the non-vectored lines, only transmit PSD spectra can be shaped to mitigate crosstalk and the channel transfer matrix H_{11}^n denotes an interference channel with K_1 transmitters and K_1 receivers. The crosstalk induced by the vectored lines on the non-vectored lines, denoted as H_{12}^n , cannot be cancelled and is treated as interference. On the other hand, the crosstalk induced by the non-vectored lines on the vectored lines, denoted as H_{21}^n , is cancelled using a zero-forcing generalized decision feedback equalizer (ZF-GDFE) in upstream transmission.

A. Vectored Lines

The vectored lines experience in-domain crosstalk (i.e. crosstalk from within the binder) because of the presence of non-vectored lines in the same cable. This in-domain crosstalk is spatially correlated and it can be cancelled by using a zero-forcing generalized decision feedback equalizer (ZF-GDFE) [3], [13]. The basic idea is that the first user to be decoded detects its data in the presence of this crosstalk and then estimates the crosstalk after detection is complete. So, the subsequent users to be decoded will see little or no crosstalk. The received signals on the vectored lines can be represented as

$$\begin{aligned} \mathbf{y}_2^n &= H_{22}^n \mathbf{x}_2^n + \underbrace{H_{21}^n \mathbf{x}_1^n}_{\tilde{\mathbf{z}}_2^n} + \mathbf{z}_2^n \\ &= H_{22}^n \mathbf{x}_2^n + \tilde{\mathbf{z}}_2^n, \end{aligned} \quad (2)$$

where $\tilde{\mathbf{z}}_2^n$ denotes the in-domain crosstalk and the background noise. No source of alien crosstalk (i.e. crosstalk from outside the binder) is assumed to be present.

The in-domain crosstalk on the vectored lines is cancelled by a noise-whitening filter, which is information theoretically lossless. The noise-whitening filter is $\Sigma_z^{-1/2}$, where Σ_z is the noise covariance matrix given by $\Sigma_z = H_{21}^n \mathbb{E}[\mathbf{x}_1^n (\mathbf{x}_1^n)^H] (H_{21}^n)^H + \Sigma_z$ and $(\cdot)^H$ is the hermitian operator. After noise-whitening, the equivalent channel for vectored lines becomes $\bar{H}_{22}^n = \Sigma_z^{-1/2} H_{22}^n$. Let the QR decomposition of the equivalent channel \bar{H}_{22}^n be given by $\bar{H}_{22}^n = \bar{Q}^n \bar{R}^n$ for a fixed decoding order. Then, the SINR for user u on subchannel n using a ZF-GDFE at the receiver is given by

$$g_u^n = (\bar{R}_{u,u}^n)^2, \quad (3)$$

where $\bar{R}_{u,u}^n$ is the u -th diagonal element of matrix \bar{R}^n .

The zero-forcing generalized decision feedback equalizer (ZF-GDFE) [13] is applied at the co-located receivers. In general, the DSL channel for upstream transmission is column-wise diagonally dominant (CWDD) [1] and zero-forcing linear equalizer (ZF-LE) has similar performance to ZF-GDFE. However, when the channel and the noise whitening filter are combined together, the equivalent channel matrix is no longer CWDD because of the in-domain crosstalk. So, the non-linear receiver structure of zero-forcing generalized decision feedback equalizer (ZF-GDFE) [13] gives better performance compared to ZF-LE. The subchannel SINRs for a ZF-GDFE depend on the ordering of QR decomposition, which means adopting different orderings over the tones produces various rate tuples and different decoding orders for the users. In this

paper, a fixed decoding order is assumed for the users for the sake of simplicity, though the results of this paper can be extended to include the optimization of the decoding orders.

B. Non-Vectored Lines

For the upstream transmission on the non-vectored lines, no signal-level coordination is possible, but the transmit PSD spectra can be optimized using DSM techniques such as OSB [8], IWF [7] etc. Each user experiences crosstalk from $(K_1 - 1)$ non-vectored users and vectored DSL system of K_2 lines. The channel signal-to-interference-plus-noise ratio (SINR) of non-vectored user u on subchannel n is expressed as

$$g_u^n = \frac{|h_{u,u}^n|^2}{\sum_{\substack{v=1 \\ v \neq u}}^{(K_1+K_2)} p_v^n |h_{u,v}^n|^2 + (\sigma_u^n)^2}, \quad (4)$$

where the direct channel of user u on subchannel n is denoted as $h_{u,u}^n$, while the crosstalk channel from user v to user u is denoted as $h_{u,v}^n$. The energy transmitted by user v on subchannel n is denoted as p_v^n .

The number of bits for any user u on subchannel n can be expressed as

$$r_u^n = \log_2 \left(1 + \frac{p_u^n g_u^n}{\Gamma} \right), \quad (5)$$

where Γ is the gap to capacity of the code [13] plus the SINR margin used for protection against unexpected noise. The data-rate for any vectored user u is then given by

$$R_u = \sum_{n=1}^N r_u^n = \sum_{n=1}^N \log_2 \left(1 + \frac{g_u^n p_u^n}{\Gamma} \right), \quad (6)$$

where $u \in \{K_1 + 1, \dots, K_1 + K_2\}$, and g_u^n is given by (3). The data-rate of any non-vectored user u is given by

$$R_u = \sum_{n=1}^N \log_2 \left(1 + \frac{|h_{u,u}^n|^2 p_u^n}{\Gamma \left(\sum_{\substack{v=1 \\ v \neq u}}^{(K_1+K_2)} p_v^n |h_{u,v}^n|^2 + (\sigma_u^n)^2 \right)} \right), \quad (7)$$

substituting g_u^n using (4) where $u \in \{1, \dots, K_1\}$.

III. ITERATIVE VS OPTIMUM DSM TECHNIQUES

In the mixed binder of vectored and non-vectored lines, the vectored lines can cancel the crosstalk from non-vectored lines, but the non-vectored lines can be victims of severe crosstalk. So, the design objective is to maximize the weighted sum-rate of the non-vectored lines while satisfying the target-rate constraints of the vectored lines and the total power constraints of all the lines.

A. MixIWF

The vectored and the non-vectored DSL access nodes may optimize the transmit PSD spectra of the vectored and non-vectored DSL lines independently using optimum DSM techniques (Algorithm 1). This is the state-of-the-art solution because optimum DSM techniques have been developed for both vectored and non-vectored DSL systems independently.

For the vectored DSL system, ZF-GDFE is applied and sub-channel SINRs are obtained for a fixed decoding order.

Then, each vectored user can independently waterfill on these subchannel SINRs to meet its target-rate-constraints (6) while satisfying the total power constraints using fixed-margin water-filling solution [3], [13].

The non-vectored DSL access node can maximize the weighted sum-rate of the non-vectored users subject to power constraints using optimum DSM techniques such as Optimum Spectrum Balancing (OSB) [8] or a distributed DSM technique such as Iterative Water-filling (IWF) [7] or Multi-level Water-filling (MLWF). IWF achieves performance close to OSB for all non-vectored lines of equal length [8], but achieves significantly lower data-rates for long non-vectored lines when some non-vectored lines are short and others are long (near-far scenarios). MLWF [14] is a low-complexity algorithm achieving performance close to OSB even in near-far scenarios.

When the vectored and non-vectored DSL access nodes optimize their systems independently, the transmit PSD spectra will converge in an iterative manner. This algorithm is summarized by Algorithm 1 and is referred to as Mixed-binder Iterative Water-filling (MixIWF) in this paper.

Algorithm 1 Mixed-binder Iterative Water-filling (MixIWF)

- 1: Initialize PSD: $p_k^n = 0 \quad \forall n, k$.
 - 2: For the non-vectored DSL system, run OSB [8] (or low-complexity MLWF [14]) to maximize the weighted sum-rate of the users subject to the total power constraints.
 - 3: For the vectored DSL system, apply ZF-GDFE to get sub-channel SINRs g_k^n and run fixed-margin Levin-Campello Water-filling algorithm [15] to achieve the target-rates and meet a given target SNR margin [13].
 - 4: Repeat 2 and 3 until data-rates of all the lines converge.
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B. MixOSB

The joint optimization problem for crosstalk management in the mixed binder of vectored and non-vectored lines can be expressed as

$$\begin{aligned} & \underset{\{p_k^n\}}{\text{maximize}} && \sum_{k=1}^{K_1} \theta_k R_k \\ & \text{subject to} && R_k \geq R_k^{\text{target}} \quad \forall k \in \{K_1 + 1, \dots, K_1 + K_2\}, \\ & && \sum_{n=1}^N p_k^n \leq P_{\text{tot}} \quad \forall k \\ & && 0 \leq p_k^n \leq S_k^n \quad \forall n, k \\ & && 0 \leq r_k^n \leq b^{\text{cap}} \quad \forall n, k \end{aligned} \quad (8)$$

Here θ_k is the relative weight given to the data-rate for k -th user for the weighted sum-rate maximization of the non-vectored users. R_k^{target} denotes the target-rate for k -th user, where the target-rates are specified only for the vectored users. The total transmit power is constrained to be P_{tot} for each user. The transmit power on each subchannel n obeys a PSDMask constraint given by S_k^n for k -th user and the maximum number of bits on any subchannel is b^{cap} [5].

The data-rates $\{R_k\}$ and the bit-allocations $\{r_k^n\}$ are expressed in terms of $\{p_k^n\}$ in (8) using (6) and (7). Note

$$\begin{aligned}
& \underset{\{p_k^n\}}{\text{maximize}} && \sum_{k=1}^{K_1} \theta_k \sum_{n=1}^N \log_2 \left(1 + \frac{|h_{k,k}^n|^2 p_k^n}{\Gamma \left(\sum_{\substack{v=1 \\ v \neq k}}^{(K_1+K_2)} p_v^n |h_{k,v}^n|^2 + (\sigma_k^n)^2 \right)} \right) - \sum_{k=1}^{(K_1+K_2)} \lambda_k \left(\sum_{n=1}^N p_k^n - P_{\text{tot}} \right) \\
& && + \sum_{k=K_1+1}^{(K_1+K_2)} w_k \left(\sum_{n=1}^N \log_2 \left(1 + \frac{g_k^n p_k^n}{\Gamma} \right) \right) - R_k^{\text{target}} \\
& \text{subject to} && 0 \leq p_k^n \leq S_k^n \quad \forall n, k, \quad 0 \leq r_k^n \leq b^{\text{cap}} \quad \forall n, k
\end{aligned} \tag{12}$$

that the subchannel SINRs g_k^n for the vectored users are not known in terms of a closed-form expression in p_k^n and the optimization problem defined in (8) is non-convex in the optimization variables $\{p_k^n\}$ because of the interference-channel characterization.

To solve this problem globally and optimally, an algorithm very similar to optimal spectrum balancing (OSB) algorithm [8] can be used. This algorithm is referred to as Mixed-binder Optimum Spectrum Balancing (MixOSB). The basic strategy is to transform the spectrum optimization problem (8) into the dual domain by forming its Lagrangian dual as defined in (12) and decompose the dual problem into tonal sub-problems using Lagrangian dual decomposition. For each set of non-negative and fixed lagrangian multipliers $\{w_k\}$ and $\{\lambda_k\}$, the tonal subproblem is to maximize

$$\sum_{k=1}^{K_1} \theta_k r_k^n + \sum_{k=K_1+1}^{K_1+K_2} w_k r_k^n - \sum_{k=1}^{K_1+K_2} \lambda_k p_k^n \tag{9}$$

on each subchannel n subject to the constraints given in (12). This maximization is done on each subchannel n using an exhaustive search over all possible values of $\{p_1^n, \dots, p_{(K_1+K_2)}^n\}$. The optimal lagrangian multipliers $\{w_k\}$ and $\{\lambda_k\}$ are found by a nested bisection search on the search space for $(\lambda_1, \dots, \lambda_{(K_1+K_2)}, w_{(K_1+1)}, \dots, w_{K_1+K_2})$. The computational complexity of MixOSB is linear in the number of tones N and exponential in the number of users $(K_1 + K_2)$. So, when the users is large, MixOSB is computationally very expensive for implementation in an SMC. Further details of the optimization algorithm are omitted here because of space constraints, but they are similar to OSB [8][16].

C. Comparison

In mixed binder of short vectored and long non-vectored lines, simulation results in Fig. 4 and 5 show that MixIWF achieves significantly lower data-rates for non-vectored lines compared to MixOSB. This is because the non-vectored lines are crosstalk-limited when the vectored lines in the same binder are running at very high data-rates. These trade-offs are similar to the ones observed in non-vectored DSL systems, where Iterative Water-filling is known to be sub-optimal when some non-vectored lines in the binder are short and others are long (commonly referred to as near-far scenario). This shows that joint DSM techniques have better performance in mixed binders where the vectored lines are short and the non-vectored lines are long.

IV. MIXED-BINDER MULTI-LEVEL WATER-FILLING

MixOSB is computationally very complex for practical implementations. Therefore, a low-complexity Mixed-binder Multi-level Water-filling (MixMLWF) algorithm is proposed

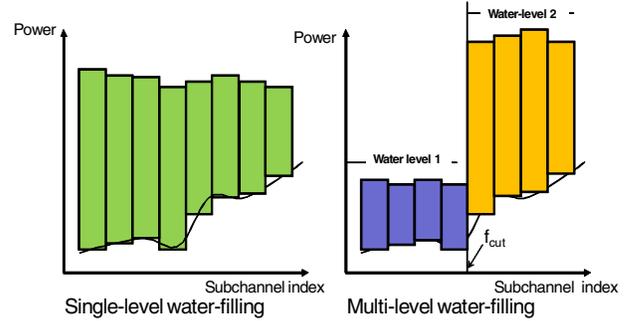


Figure 2. Comparison of Water-filling vs. Multi-level Water-filling (MLWF).

for such mixed-binders of short vectored and long non-vectored lines based on [14]. MixMLWF is low-complexity, practically implementable, and achieves performance close to MixOSB. It has a distributed implementation with some guidance from SMC for each user.

MixMLWF uses a simple spectrum adjustment procedure on top of the fixed-margin water-filling algorithm run by the vectored users to reduce their interference into the non-vectored lines and obtain an OSB-style spectrum. The short vectored DSL lines first run fixed margin water-filling on the sub-channel SINRs obtained from ZF-GDFE (3), and then move bits from below the cut-off frequency f_{cut} (see Fig. 2) to above this cut-off frequency to avoid emitting excessive interference to the long non-vectored line's only bit-loading frequency band. This process of moving information continues until further move of bits will violate PSDMask or power constraints. The resultant spectra will look like two water-filling bands as in Fig. 2. The algorithm can also be extended to three or more water-levels, and the bits are always moved first from the band, which is causing maximum interference to the non-vectored lines, to the band, which is causing minimum interference to the non-vectored lines, until total power or PSDMask constraints limit further spectrum adjustments in such bands. Algorithm 2 summarizes the Mixed-binder Multi-level Water-filling (MixMLWF) algorithm with 2 water levels for mixed binders of vectored and non-vectored lines.

The cut-off frequencies need to be determined by the SMC before the MixMLWF algorithm can perform its bit-moving procedures. A simple gradient search algorithm can be used to search for the cut-off frequency for two water-levels while maximizing the weighted sum-rate of the non-vectored users and satisfying the target-rate of the vectored users, as summarized in Algorithm 3. For three or more water-levels, iterative coordinate descent can be applied on top of Algorithm 2 (see [14] for details).

After the cut-off frequencies are determined, the user-priority indication (standardized in [5]) can be used to indicate that MixMLWF is desired from the vectored users, and the cut-

off frequencies are sent to the vectored DSL lines by lowering the PSDMASK setting in the band, which is causing maximum interference, by a few dB compared to the band, which is causing less interference to the non-vectored users (via the standardized capability of PSDMASK setting in ITU standard G.vector [5]). In practice, two or three bands suffice to achieve a good performance.

Algorithm 2 Mixed-binder Multi-level Water-filling

- 1: Initialize PSD: $p_k^n = 0 \quad \forall n, k$.
 - 2: For the non-vectored DSL system, run low-complexity MLWF [14] to maximize the weighted sum-rate of the users subject to the total power constraints.
 - 3: For the vectored DSL system, apply ZF-GDFE to get sub-channel SINRs g_k^n and run fixed-margin Levin-Campello Water-filling algorithm [15] to achieve the target-rates and meet a given target SNR margin [13].
 - 4: For each vectored user, the bands of tones (ordered according to bands causing maximum to minimum interference to non-vectored users) are determined based on the $L - 1$ f_{cut} (s) determined by the SMC.
 - 5: **while** $p_k^n < S_k^n, \sum_{n=1}^N p_k^n < P_{tot} \quad \forall k \in \{K_1+1, \dots, K_1+K_2\}$ **do**
 - 6: For the vectored user, remove bits from the tones of bands causing maximum interference and place them into the positions of least incremental energy on the tones of the band causing minimum interference.
 - 7: **end while**
 - 8: Repeat 2-7 until data-rates converge for all users.
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Algorithm 3 Centralized Cut-off Frequency Search Algorithm for two water-levels

- 1: Initialize the gradient step size $\Delta f = \Delta f^{(0)}$ and the cut-off frequency $f_{cut} = f_{cut}^{(0)}$ for all the vectored users
 - 2: **while** $\Delta f \geq \Delta f_{min}$ **do**
 - 3: $f_{cut}^+ = f_{cut} + \Delta f, f_{cut}^- = f_{cut} - \Delta f$.
 - 4: Evaluate the data-rate of the vectored and non-vectored users $R_k(f_{cut}), R_k(f_{cut}^+)$ and $R_k(f_{cut}^-)$.
 - 5: **while** target-rate constraints are satisfied for the vectored users and total-power constraints are met, **do**
 - 6: If the weighted sum-rate of non-vectored users $\sum_{k=1}^{K_1} \theta_k R_k$ is increased by changing f_{cut} to either f_{cut}^+ or f_{cut}^- , choose the one that gives the most improvement as the f_{cut} for next iteration, i.e., set f_{cut} to f_{cut}^+ or f_{cut}^- .
 - 7: Quit if the weighted sum-rate of non-vectored users cannot be improved further.
 - 8: **end while**
 - 9: Decrease step-size Δf (e.g., $\Delta f = \frac{\Delta f}{2}$).
 - 10: **end while**
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V. SIMULATION RESULTS

Simulations are performed for mixed binder scenarios with vectored DSL and non-vectored DSL (VDSL2) using simula-

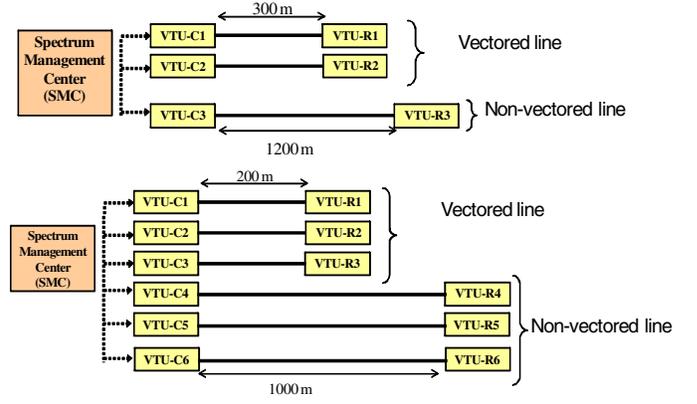


Figure 3. Mixed-binder VDSL2 Upstream examples with (a) (top) 2 short vectored lines (300 m) and 1 long non-vectored line(1200 m) (b) (bottom) 3 short vectored lines (200 m) and 3 long non-vectored line (1000 m)

Table I
VDSL2 SIMULATION PARAMETERS.

Parameter	VDSL2 Upstream
Subchannel Width	4.3125 kHz
Maximum Power	14.5 dBm
Coding Gain	3 dB
Target Margin	6 dB
Gap	9.8 dB
Band-plan	VDSL2, 17MHz
Bit-cap	15
Line type	26 AWG

tion parameters defined in Table I. For upstream transmission in VDSL2, VDSL spectrum profile 17a is used which allows the use of upstream bands US0 (25kHz-138kHz), US1 (3.75 MHz-5.2 MHz), and US2 (8.5 MHz-12MHz). In MixMLWF algorithm, three bands or two cut-off frequencies are considered. The static-band MixMLWF means the three upstream bands for MixMLWF are US0, US1, and US2 and it does not search for the optimal set of cut-off frequencies, while dynamic-band MixMLWF searches for the optimal set of cut-off frequencies using Algorithm 3.

To reduce the computational burden of MixOSB, two short vectored lines of 300m each and one long non-vectored line of 1000m is considered (Fig. 3(a)). The achievable rate-region of non-vectored lines versus vectored lines is shown in Fig. 4 comparing UPBO, MixIWF, MixMLWF and MixOSB. UPBO refers to upstream power back-off methods as defined in [6] for VDSL which allow the vectored VDSL lines to lower the PSD and back-off in power. The two short vectored lines have symmetric rate targets. In this mixed binder, UPBO and MixIWF have the worst performance, while both static-band and dynamic-band MLWF achieve substantially higher data-rates compared to MixIWF. For example, when the average rate of the vectored lines is 50 Mbps, the data-rate of non-vectored line is about 2 times higher than MixIWF by using static-band MLWF and is more than 3 times higher than MixIWF by using dynamic-band MixMLWF. The rate-region of MixMLWF and MixOSB is very close and the loss in data-rate of non-vectored line by using MixMLWF is less than 0.75 Mbps for any average rate of the vectored lines. Continuous bit-loading in MixOSB versus discrete bit-loading in other

algorithms results in a difference of about 0.25 Mbps at zero-target-rate of the vectored users. The penalty for not finding the optimal cut-off frequencies is high and the data-rate of non-vectored line using static-band MixMLWF is significantly lower than dynamic-band MixMLWF when the target-rates of vectored lines are more than 40 Mbps.

In the next example, a mixed binder in upstream VDSL2 (Fig. 3(b)) with three short vectored lines (200m) and three longer non-vectored lines (1000m) are considered. The achievable rate-region in Fig. 5 shows the average rate of non-vectored lines versus the vectored lines for MixIWF and MixMLWF. The data-rates using MixOSB are not computed because of computational complexity issues. Both static-band and dynamic-band MixMLWF have almost similar performance. The non-vectored user is achieving data-rates in the range 0-8.5 Mbps and the gain in average data-rate of non-vectored user by using MixMLWF over MixIWF is as large as 4-5.5 Mbps when the target-rates of vectored lines are high and non-vectored long lines are severe victims of crosstalk. In this case, there is no penalty for not searching the optimal cut-off frequencies.

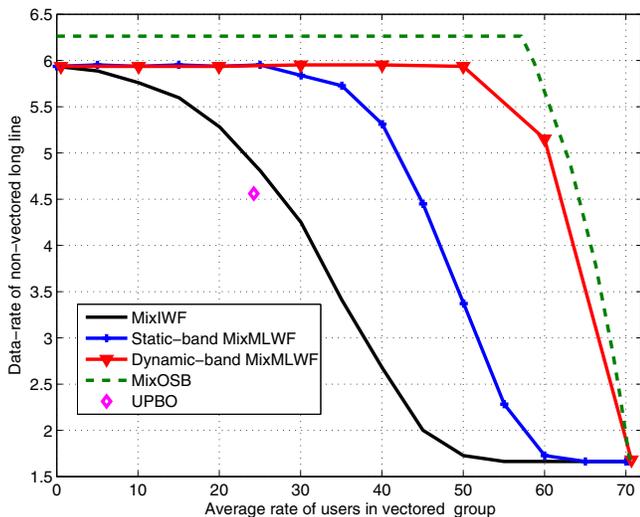


Figure 4. Rate-region for the mixed binder in Fig. 3(a) using UPBO, MixIWF, MixMLWF and MixOSB.

VI. CONCLUSIONS

Mixed-binder Optimum Spectrum balancing (MixOSB) is presented in this paper to compute optimal transmit PSD spectra for mixtures of vectored and non-vectored lines in a binder. Such mixed-binder scenarios may occur as Vectored DSL begins to be deployed in the next few years. In mixed-binders with short vectored DSL lines and longer non-vectored DSL lines, applying DSM techniques independently to the vectored and non-vectored DSL systems is found to be strictly suboptimal to MixOSB. This highlights the requirement for managing the crosstalk induced by vectored lines on non-vectored lines at an SMC using DSM techniques such as MixOSB. Since MixOSB is computationally expensive, a practically implementable MixMLWF algorithm is also proposed with performance similar to MixOSB.

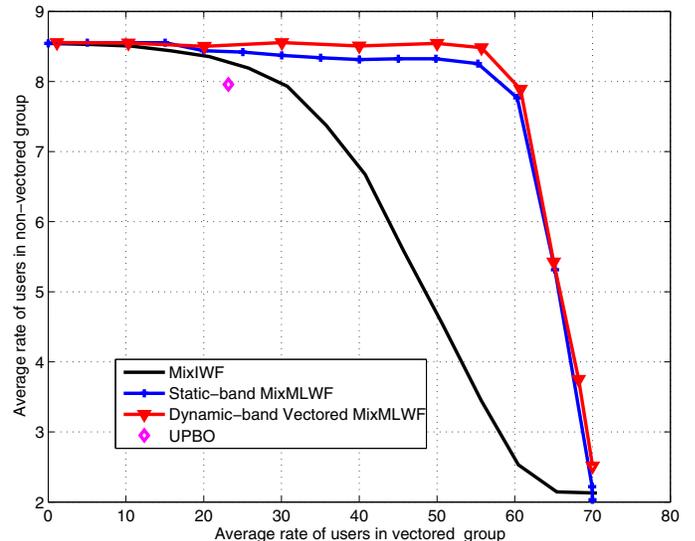


Figure 5. Rate-region for the mixed binder in Fig. 3(b) using UPBO, MixIWF and MixMLWF.

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